Title: **Solar Particle Event Modeling Compared To Satellite Data**

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Abstract: Solar protons are the primary source of ionizing radiation for certain missions. Several models of these solar energetic proton events exist, giving different results. We compare three models with satellite data to assess these differences.

Solar particle event (SPE) protons are a primary driver of ionizing dose for shielded components in long-duration interplanetary flights. Several models exist for estimating SPE flux and fluence given trajectory factors and time in solar maximum and solar minimum. A confidence interval is used ranging from fiftieth percentile (50%) to 99% depending on risk tolerance. A 95th percentile (95%) confidence interval is the level recommended by NASA for a number of scenarios, such as in the Cross-Program Design Specification for Natural Environments SLS-SPEC 159 (DSNE). Total ionizing dose is calculated from the proton flux/fluence model output using one of several dose-depth tools, such as Shieldose-2. However, if one compares the output of several different SPE models they will find the results diverge at higher confidence intervals. This can lead to confusion as to what the anticipated risk is, particularly in marginal cases. We examine three commonly used SPE models and compare historical satellite observations with their output to assess these differences.

The three models we have examined are the Jet Propulsion Laboratory model (JPL-91 or JPL) [Feyman et al 1990], the Emission of Solar Protons model (ESP) [Xapsos et al 1999], and the Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment (SAPPHIRE) [Jiggens et al 2018] model as implemented in the SPENVIS online-access system at https://www.spenvis.oma.be/. Each model uses different assumptions to calculate fluences from historical data, and in the SPENVIS implementation each uses different data sets. Our test scenario used in all three models is 7 years at solar maximum in interplanetary space, taking confidence intervals of 50%, 65%, 75%, 85%, and 95%.

For satellite data we have used seven-year increments around solar maxima, taken as +/-3.5 years from peak sunspot activity. We have used data from both International Monitoring Platform (IMP) missions found at https://omniweb.gsfc.nasa.gov/ and the Geostationary Operational Environmental Satellites (GOES) found at https://www.ngdc.noaa.gov/stp/satellite/goes/index.html. IMP data used ranges from years 1967 to 2004, encompassing four successive solar maxima. GOES data used ranges from years 1988 to 2017, encompassing the successive solar maxima. The two overlapping solar maxima were used to scale the IMP data to the GOES data, giving us five successive solar maxima for comparison.

In order to reduce the effects of random variation, only the total fluence was used for comparison. Differential fluence was used to facilitate dose calculation. Figures 1-2 show the satellite-derived differential fluences for the five solar maxima compared to the ESP and SAPPHIRE models, respectively. The model data consists of seven-year differential fluences at the 50%, 75%, and 95% confidence intervals.

Comparing these five satellite-derived spectra with the three SPE models, the shape of the observed SPE differential spectra are generally different from the model SPE spectra. However, ESP's 95% fluence is above or approximately equal to all satellite-derived fluences. This is to be expected as with only five maxima to consider, it is unlikely any of them would be a 95th percentile case if we could consider a much larger number of solar cycles. JPL and SAPPHIRE 95% fluences are below some observed fluences at some energies. These are low energies, with one exception, so caution is recommended when energies below 2 MeV are significant. SAPPHIRE at energies above about 20 MeV notably has multiple satellite-derived spectra that fall in the 75-95% band. While it is possible that multiple satellite-derived spectra would fall in this band given many more solar cycles, that scenario is sufficiently unlikely that it raises the possibility of insufficient conservatism for safety purposes if the SAPPHIRE model is used.

We next ran the three model and five satellite-derived SPE spectra through Shieldose2 in sphere mode to obtain deposited dose in silicon for aluminum shielding with thickness from 1 to 10 mm in 1 mm increments. Using deposited dose as a metric provides a more direct comparison to the quantity related to SPEs that is of most interest for radiation safety of shielded components. Tables 1-2 show sample results for 4 mm Al shielding. We see from this that, within tolerances, all three models show a 50th percentile that is above two of the satellite-derived values. As 50th percentile represents a median, the 50th percentile values are expected to be above two or three out of five satellite-derived values. At 95% all predicted doses that are, as expected, above the highest satellite-derived dose. ESP's 95% prediction is notably four times the highest satellite-derived value. SAPPHIRE is by far the lowest estimate, with JPL somewhere between. With only five solar cycles available, none of them can be definitively ruled out. The ESP model is especially conservative, which is useful for radiation safety purposes. This is thought to be due to the different method of percentile estimate it uses [Xapsos et al. 1999]. However, if propagated through further modelling or simulation, undesirably over-estimated values may result.

The analysis outlined here provides useful benchmarks for use of models of SPEs. Those using these SPE models may wish to choose a particular model depending on their purposes, such as using ESP if they desire to build conservatism in at the spectrum level. As data on the current solar cycle becomes available, this analysis can be refined further.

References:

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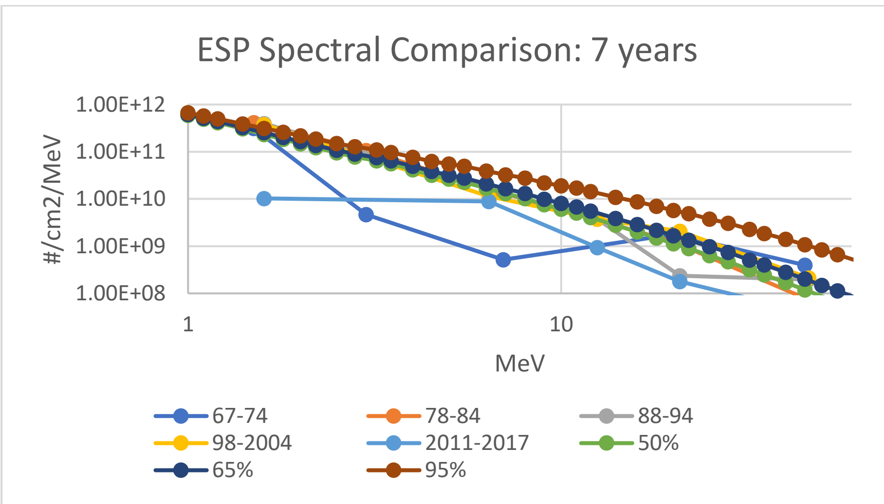

Figure 1: ESP spectra compared with satellite data.

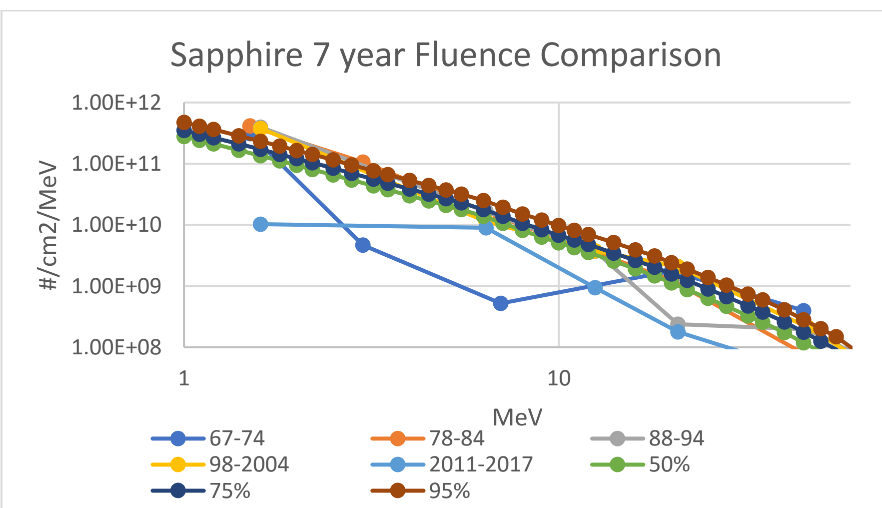

Figure 2: SAPPHIRE spectra compared with satellite data.

Percentile	50% (Mean)	75	85	95
Sapphire	2.23	3.28	3.93	5.20
ESP	2.21	5.20	8.21	17.6
JPL91	2.05	3.51	4.95	10.0

Table 1: SPE model doses in Si behind 4 mm Al shielding for 7 years in solar maximum, in kRads.

Solar Cycle	Dose (kRads)
20	3.01
21	0.863
22	2.37
23	4.03
24	0.730

Table 2: Satellite-derived doses in Si behind 4 mm Al shielding for 7 years around solar maxima by solar cycle. Dose is in kRads.